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Enabling 4-Dimensional Trajectory Based Operations of Manned and Unmanned Aircraft

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Abstract. This article presents the conceptual design of an innovative ground-based Air Traffic Management (ATM) system providing automated 4-Dimensional Trajectory (4DT) Planning, Negotiation and Validation (4-PNV) functionalities. The 4-PNV system is conceived to operationally deploy the multi-objective optimisation, negotiation and validation of 4DT intents in combination with Next Generation Flight Management Systems (NG-FMS) on board manned aircraft and Next-Generation Mission Management Systems (NG-MMS) for Remotely Piloted Aircraft Systems (RPAS). In this article we focus on the 4-PNV functionalities required for mixed fleet optimized Arrival Management (AMAN) operations. Simulation case studies in representative complex scenarios show that the adopted negotiation algorithms achieve feasible, efficient and safe 4DT solutions well within the timeframe of online tactical rerouting tasks, meeting the set design requirements.

Introduction

In order to achieve the ambitious objectives set by national and international organisations for capacity, efficiency, sustainability and safety of future flight operations, it will be essential to fully exploit the available Navigation and Guidance System (NGS) technologies in the online Air Traffic Management (ATM) context. The adoption of 4-Dimensional Trajectories (4DT) in an Intent Based Operations (IBO) environment has been envisaged as a key step for such enhanced resource exploitation. Novel Communications, Navigation, Surveillance and ATM (CNS/ATM) systems are being developed to enable the 4DT-IBO. As such, the online generation, validation, execution and monitoring of optimised 4DT intents is one of the prominent and growing applications in the CNS/ATM domain. Although the optimisation of flight trajectories has been studied for a long time and various numerical solution strategies have been proposed, significant practical gains in the operational context are still to be attained due to the limitations of the available air traffic and airspace models. As mentioned in our previous research, one of the major obstacles is the limited modelling of the CNS/ATM system dynamics [1-4]. The inability to handle the highly dynamic nature of the system and the associated uncertainties in a predictive real-time manner results in overall system inefficiencies. Therefore, the dynamics of the system have to be fully considered and implemented in the models in order to evolve the design of CNS/ATM and Avionics (CNS+A) systems that will finally unleash the full potential of 4DT optimisation. In this perspective, earlier studies addressed the development of automated ATM systems [5-9]. This paper expands the development of the ground-based 4DT Planning, Negotiation and

Validation (4-PNV) ATM system [2-4], which is a substantially innovative evolution intended to introduce online 4DT management functionalities including an effective multi-objective 4DT optimisation strategy suitable for both manned aircraft and Remotely Piloted Aircraft Systems (RPAS) platforms.

CNS+A Concept of Operations

The CNS+A concept of operations in the online 4DT-IBO context is schematically represented in Fig. 1. The 4-PNV system features 4DT planning, data exchange and negotiation/validation with the Next Generation of Flight Management Systems (NG-FMS) on board manned aircraft and Mission Management Systems (NG-MMS) on board RPAS [10-12]. The optimised 4DT intents generated by the NG-FMS and NG-MMS are downlinked to the ground-based 4-PNV system via a Next Generation Aeronautical Data-Link (NG-ADL). Several 4DT intents are generated by each NG-FMS/MMS, providing multiple options to identify a conflict free solution for each traffic in real-time [3], hence decreasing the length of negotiation time and reducing the need for ATM to calculate optimal 4DT remotely. Once an optimal conflict-free 4DT has been identified, reviewed and approved by the human Air Traffic Control Operators (ATCO), the 4DT validation is accomplished and a clearance is uplinked to the NG-FMS/MMS. When valid 4DT cannot be identified among the NG-FMS/NG-MMS intents, the 4-PNV based on the performance weightings defined as part of an automation-assisted Collaborative Decision-Making (CDM) process calculates a new family of optimal 4DT and uplinks them to the aircraft. The NG-FMS/MMS then analyses the received 4DT, assessing the compliance with aircraft performance and

operational envelope, and presents them to the flight crew/remote pilots in enhanced Human-Machine Interface and Interactions (HMI²) formats. After reviewing and selecting the preferred solution, the

flight crew/remote pilots issue a confirmation to the 4-PNV. The increased automation allows more aircraft to fly optimal flight paths, limiting the intervention of the controllers to higher-level and emergency decisions.

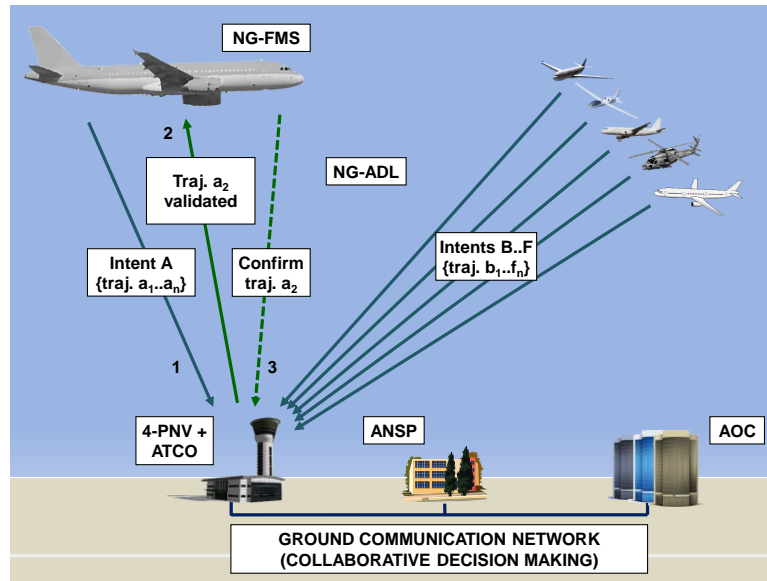


Figure 1. Online CNS+A concept of operations.

4-PNV Model Requirements

The 4-PNV model for “single attempt” negotiation of 4DT is based on the following requirements [3]:

1. The system shall identify a conflict-free 4DT for each traffic;
2. The system shall have a high computational efficiency, compatible with the online tactical operational timeframe defined in [2];
3. The system shall be able to negotiate and validate the 4DT intents of multiple aircraft, with multiple equipage in dense air traffic conditions;
4. The system shall reduce human operator’s workload and improve his situational awareness;
5. The system shall improve the overall optimality of air traffic in terms of environmental and economic sustainability objectives.

4-PNV System Architecture

The online processes are distributed across the NG-FMS/NG-MMS, Airline Operations Centres (AOC), Air Navigation Service Providers (ANSP), regional Air Traffic Flow Management (ATFM) centres and ATM units. The 4-PNV analyses and selects the globally optimal combination of intents to best achieve global objectives, whilst ensuring that the validated 4DT are free from traffic conflicts, known or likely weather hazards and congested sectors. Fig. 2 depicts a schematic architecture of the 4-PNV system.

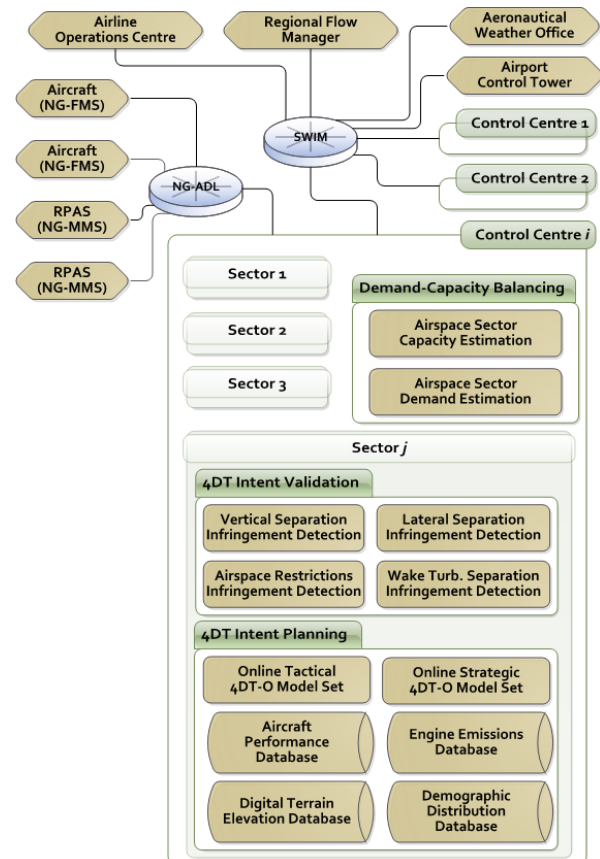


Figure 2. 4-PNV architecture.

4D Trajectory Optimisation

The real-time multi-objective trajectory optimisation algorithms implemented in the 4-PNV system adopt the same models implemented in the NG-FMS/MMS. The aircraft dynamic parameters are shared between the NG-FMS/MMS and the 4-PNV through the NG-ADL, along with the relevant aircraft states, to ensure synchronisation and mathematical consistency. The current 4DT optimization algorithms are based on direct methods with pseudo-spectral transcription. The adopted three degrees of freedom (3DOF) point-mass dynamics model with variable mass is:

$$\dot{\mathbf{x}} = \begin{cases} \dot{v} = \frac{\tau \cdot T_{CL} - D}{m} - g \sin \gamma \\ \dot{\gamma} = \frac{g}{v} \cdot (N \cos \mu - \cos \gamma) \\ \dot{\chi} = \frac{g}{v} \cdot \frac{N \sin \mu}{\cos \gamma} \\ \dot{\phi} = \frac{v \cos \gamma \sin \chi + v_{w\phi}}{R_E + z} \\ \dot{\lambda} = \frac{v \cos \gamma \cos \chi + v_{w\lambda}}{(R_E + z) \cos \phi} \\ \dot{z} = v \sin \gamma + v_{wz} \\ \dot{m} = -FF \end{cases} \quad (1)$$

Where v is the true airspeed, \mathbf{v}_w is the wind velocity vector, γ is the flight path angle, χ is the track angle, m is the aircraft mass, ϕ , λ and z are respectively the geodetic latitude, longitude and altitude, g is the gravity acceleration, R_E is the geodetic Earth radius, D is the aircraft drag, T_{CL} is the maximum climb thrust. The control variables are $\mathbf{u} = \{N, \tau, \mu\}$, which respectively represent the load factor, the throttle and the bank angle. The drag is calculated with the conventional parabolic approximation as:

$$D = \frac{1}{2} \rho v^2 S C_{D0} + \frac{2 C_{D2} m^2 g^2}{\rho v^2 S} \quad (2)$$

Where ρ is the local air density, and S, C_{D0}, C_{D2} are obtained by the Eurocontrol's Base of Aircraft Data (BADA) database and respectively represent the aircraft reference area and the two parabolic drag coefficients. The drag coefficient increases to account for flaps and landing gear are also available [13]. Adopting the formulation from BADA, the maximum climb thrust and the fuel flow of a turbofan engine are calculated as [13]:

$$T_{CL} = C_{T1} \cdot \left(1 - \frac{H_p}{C_{T2}} + C_{T3} \cdot H_p^2\right) \cdot [1 - C_{T5} \cdot (\Delta T - C_{T4})] \quad (3)$$

$$FF = \max \left[\tau C_{f1} \left(1 + \frac{v_{TAS}}{C_{f2}}\right), C_{f3} \left(1 - \frac{H_p}{C_{f4}}\right) \right] \quad (4)$$

Where $C_{T1} \dots C_{T5}$, $C_{f1} \dots C_{f4}$ are the thrust and fuel flow coefficients from the BADA empirical models [13]. The emission of a generic Gaseous Pollutant (GP) is generically modelled as:

$$GP = \int_{t_0}^{t_f} EI_{GP} \cdot FF dt \quad [\text{Kg}] \quad (5)$$

The specific carbon monoxide (CO) and unburned hydrocarbon (HC) emission indexes are empirically modelled as:

$$EI_{CO/HC} = c_1 + \exp(-c_2 \tau + c_3) \quad [\text{g/Kg}] \quad (6)$$

Similarly, the nitrogen oxides (NO_x) emission index is empirically modelled as:

$$EI_{\text{NO}_x} = c_1 \tau^2 + c_2 \tau + c_3 \quad [\text{g/Kg}] \quad (7)$$

Eq. 6 and 7 are conceived to introduce an accurate nonlinear fit of the ICAO Emissions Databank [14]. Fig. 3, 4 and 5 represent the resulting curves fitting 165 currently operating jet engines in the database.

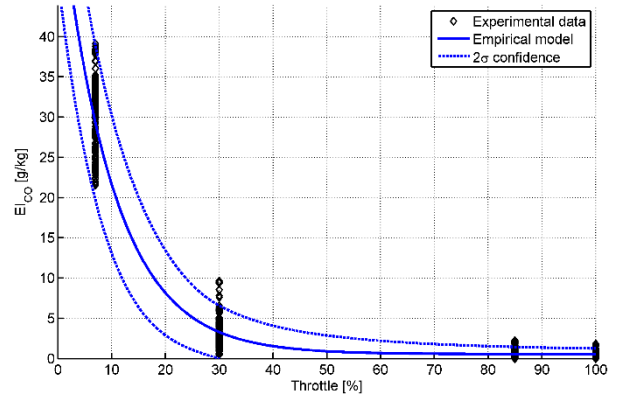


Figure 3. Nonlinear fit of the CO emission indexes.

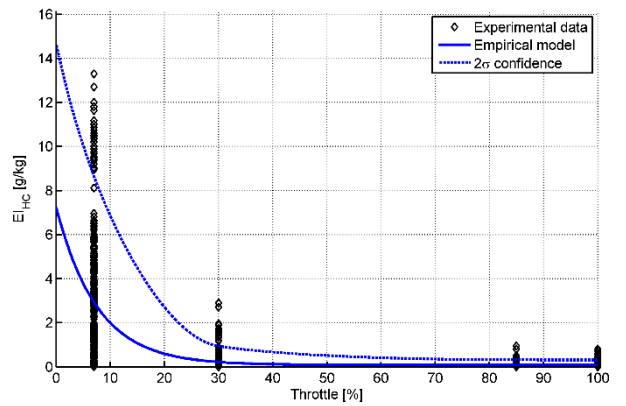


Figure 4. Nonlinear fit of the HC emission indexes.

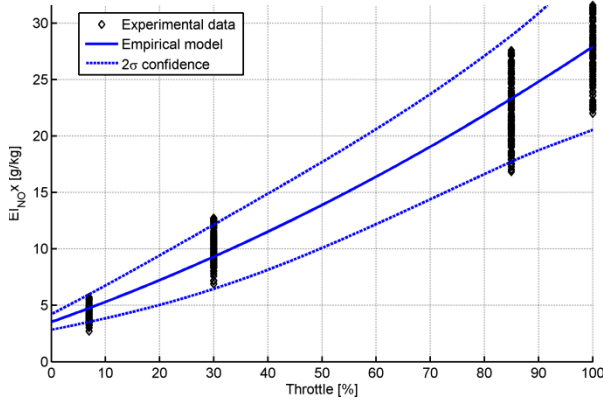


Figure 5. Nonlinear fit of the NO_x emission indexes.

Linearised models can be introduced to enhance computational performance when required. We also adopt the following generalised expression of the cost function for penalties associated with the transit through a dynamic penalty volume [2]:

$$J_i = \sum_{j=1}^{n_{sect}} \int \left[PF_{i,j} \cdot \left(\mathbf{x}(t) \cap S_j(t) \right) \right] dt \quad (8)$$

where:

$PF_{i,j}$ = Penalty Factor associated to the i^{th} objective in the j^{th} penalty volume;

$S_j(t)$ = j^{th} dynamic penalty volume.

Eq. 5 can be used with suitable forms of the Airspace Model (ASM), Condensation Trails Model (CTM), Weather State Model (WSM) and Noise Emission Model (NEM), by setting the associated penalty factors to adequate values. The computation of the portion of trajectory inside the penalty volume (Eq. 8) is supported by the Geospatial Data Abstraction Library (GDAL/OGR). The significant number of nonlinearities present in the models (aircraft dynamics, weather, etc.) generate multiple local minima in the performance indexes, severely affecting nonglobal convergence iterative methods. These limitations can be overcome through the adoption of a hybrid optimiser, with either a pattern search or an evolutionary algorithm performed as a first instance to determine the global convergence region, and subsequently a gradient based iteration to attain local optimality [2]. Our current real-time 4DT optimisation algorithm is based on gradient-based iterations with pseudo-spectral transcription, as described in [3, 12], and a hybrid extension is being implemented, by introducing a preliminary discrete pattern search.

Multi-Objective Optimality

In line with the requirements for online tactical replanning, the weighted sum method, belonging to the category of *a priori* articulation of preferences, is adopted for the pre-identification of a unified

performance index J , in a truly *a priori* multi-objective approach [2, 15]. The *a priori* multi-objective optimisation approach is conceptually represented in Fig. 6.

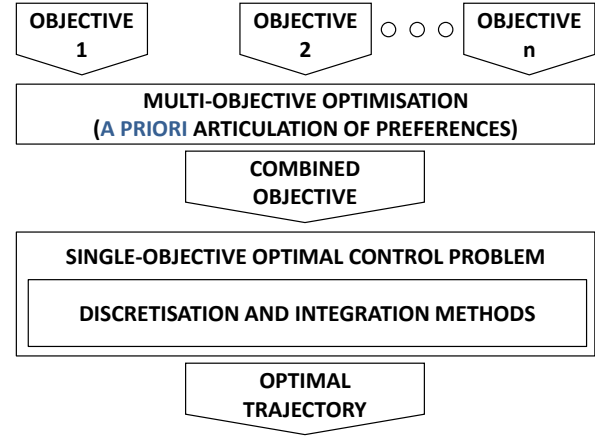


Figure 6. Block diagram of multi-objective optimisation with *a priori* articulation of preferences [2].

The performance weightings can be dynamically modified along the flight and as part of an ongoing Collaborative Decision Making (CDM) process between the AOC and ANSP when required. An example of a set of four performance weightings is illustrated in Table 1.

Table 1. Example of different performance weighting sets.

	Flight Time	Fuel Burn	Noise	Emissions	Airsp. Sector Occupancy
Priority 1	K_{A1}	K_{B1}	K_{C1}	K_{D1}	K_{E1}
Priority 2	K_{A2}	K_{B2}	K_{C2}	K_{D2}	K_{E2}
Priority 3	K_{A3}	K_{B3}	K_{C3}	K_{D3}	K_{E3}
Priority 4	K_{A4}	K_{B4}	K_{C4}	K_{D4}	K_{E4}

Multiple optimal 4DT are generated on board each traffic, and then using a rule-based algorithm, a conflict free set of trajectories is found for all aircraft.

Intent Negotiation and Validation Loops

The online tactical rerouting requirements prescribe that 4-PNV validation algorithms are to be designed to achieve *single-attempt* negotiations. A 4DT negotiation protocol was developed in EUROCONTROL's DOC

97-70-14 [5] and can be adopted to iteratively generate an optimal flight path, taking all constraints into consideration. Our customized negotiation loops were introduced in [3] and are depicted in Fig. 7 and Fig. 8, which respectively represent the 4-PNV initiated and the NG-FMS initiated loops. The shared trajectory intents include the aircraft's unique identification and model, the wake-turbulence category, and the vector of 4DT waypoints in the prescribed format. The ground-based 4-PNV system is the protagonist of the strategic online scenario as it retains a continuously updated global situational awareness, thanks to the ground network and to own predictions algorithms. Uncertainties, such as long-term forecast weather phenomena, airport closures or sectors saturations, prompt the 4-PNV to initiate a strategic replanning and negotiation by up-linking new constraints to the NG-FMS, which are then incorporated as part of the on-board 4DT optimisation. Alternatively, the 4-PNV may compute optimal 4DT and uplink them for validation by the aircraft. If, after on-board evaluations performances/constraint violations exist (e.g. turn radius, climb rate), the aircraft downlinks a rejection message together with a new intent to the 4-PNV for validation. Multiple negotiation loops are allowed in the strategic online scenario but minimised thanks to the availability of multiple 4DT intents for each aircraft. If for particular reasons the newly introduced constraints cannot be satisfied, then the negotiation may still be pursued via human direct intervention.

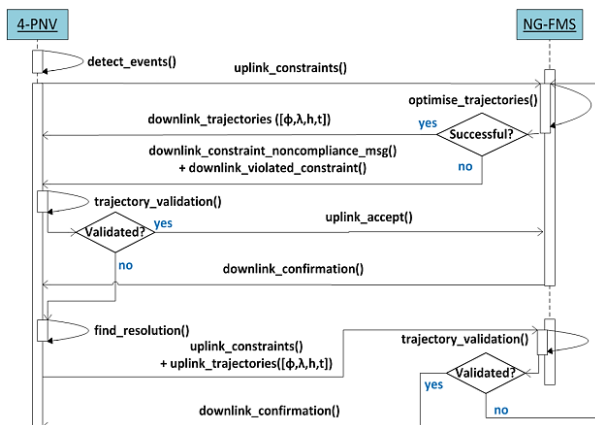


Figure 7. 4-PNV initiated 4DT Intent Negotiation/Validation Loop [3].

In the tactical online scenario, either the NG-FMS or the 4-PNV may initiate 4DT intent negotiations. The 4-PNV will act mainly as a key decision maker. The NG-FMS may initiate the trajectory negotiation due to locally detected weather changes, aircraft performance degradation, equipment failures or on-board emergency situations. Other manoeuvre-related factors such as inefficient heading changes, and unachievable climb/descent rates and altitudes due to the actual aircraft weight may also be causes of negotiation. In

the tactical online scenario, a “single-loop” negotiation is ultimately sought due to the reduced time and stringent traffic management commitments. Similarly to the strategic online, if a solution cannot be obtained through trajectory negotiation then ATCO’s and pilots’ direct intervention will be considered.

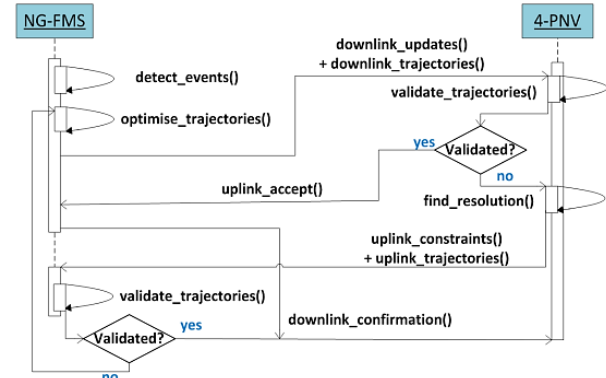


Figure 8. NG-FMS initiated 4DT Intent Negotiation/Validation Loop [3].

In order to be adopted for both strategic online and tactical online contexts, with a reference time horizon of 5 minutes, it is assumed that the total duration of optimization, negotiation and validation processes must remain under 180 seconds. Trajectories are checked for traffic conflicts and separation from hazardous phenomena. The validation algorithm assesses the lateral and vertical separation criteria and includes a simplified wake vortex modelling to assess the longitudinal separation. The Collaborative Decision Making (CDM) is substantially enhanced through the exploitation of semi-automated negotiation schemes.

Simulation and Results

The sequencing of dense arrival traffic towards a single approach procedure was extensively evaluated as a representative case study of online tactical Terminal Manoeuvring Area (TMA) operations [2]. The results of one representative simulation run are depicted in Fig. 9. The 4-PNV identifies the best arrival sequence among the available options. Longitudinal separation is enforced at the merge-point to ensure sufficient separation upon landing, and to prevent separation infringements in the approach phase itself. The 4-PNV is capable of performing point-merge at any metering point. After the initial intents have been stored in the 4-PNV, the point-merge sequencing algorithm allocates the available time slots accordingly. The assumed minimum longitudinal separation is 4 nautical miles on the approach path for medium category aircraft approaching at 140 knots, therefore the generated time slots are characterized by a 90~160 seconds separation depending on the wake-turbulence categories of two consecutive traffics.

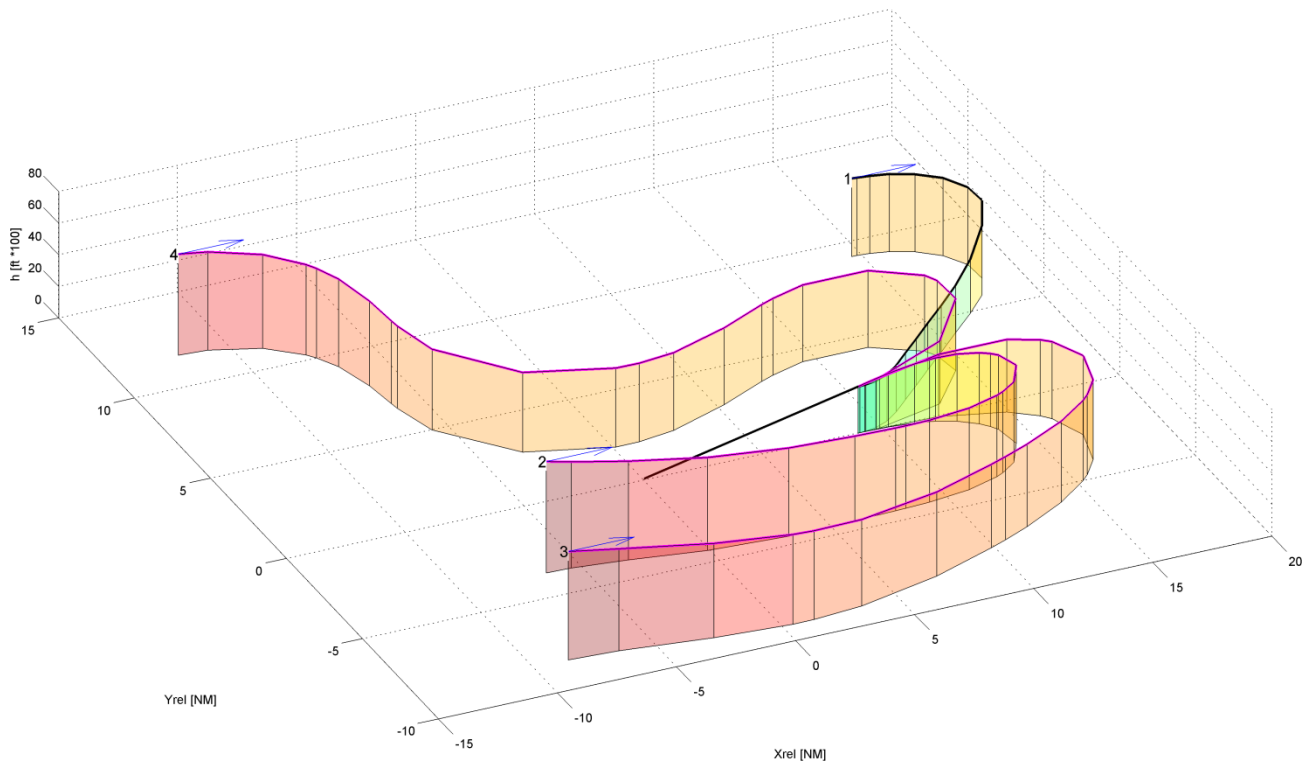


Figure 9. Validated 4DT intents in the TMA scenario.

Conclusions

This paper presented the conceptual design of a novel 4-Dimensional Trajectory Planning, Negotiation and Validation (4-PNV) system, conceived to introduce automated Air Traffic Management (ATM) functionalities in online strategic and tactical operations. The 4-PNV system is intended to operationally deploy 4-Dimensional Trajectory (4DT) Intent Based Operations (IBO) in cooperation with the Next Generation Flight Management System (NG-FMS) on board manned aircraft and Mission Management Systems (NG-MMS) for Remotely Piloted Aircraft Systems (RPAS). In line with current and likely future ATM requirements, a near-real-time negotiation scheme for dynamic rerouting was implemented. This process enables automatic planning, negotiation and validation of 4DT, in the presence of dense air traffic, whenever airspace or air traffic reorganisation is required due to tactically changing airspace conditions. Simulation case studies allowed a preliminary assessment of the 4-PNV negotiation and validation models. In high air traffic density conditions, the complete process of NG-FMS/MMS 4DT intent generation, downlink to the 4-PNV and negotiation/validation is performed in less than 180 seconds. These results meet the 5 minutes timeframe assumed for online tactical routing/rerouting tasks and make the approach feasible for quasi-real-time applications. Future research will address the implementation and evaluation of other indirect and hybrid trajectory optimisation methods, as well as

enhanced algorithms for conflict detection. The concurrent research on safety-critical obstacle avoidance and Detect-and-Avoid (DAA) systems will be highly instrumental in the implementation and assessment of efficient optimisation models for 4DT planning [16-25]. Reduced separation minima will be implemented to exploit the full potential of high-accuracy advanced Navigation and Guidance Systems (NGS) [26-35]. Further 4-PNV evolutions will also incorporate various CNS+A integrity monitoring and augmentation strategies currently being researched [36-38].

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